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TO: Mr. N.M. Thompson
Group Manager
Stations and Transmission Programs

OTTAWA OVERBROOK TS - GROUNDING SYSTEM STUDIES

P. Pillai

Ground potential rise, touch and step potentials and current splits were measured at Ottawa Overbrook TS under simulated fault conditions. Soil resistivity at the station was also tested. The results show that the station ground potential rise and touch and step potentials are within safe limits for an ultimate station fault level of 9 kA. The measurements were unable to verify whether the station fence is connected to the main station grid. Models were developed to validate and generalize the results.

1.0 INTRODUCTION

At Ottawa Overbrook TS, two 115-kV overhead lines on separate rights-of-ways (circuits K1R and A4K) supply transformers rated 75 MVA, 110/14.2/14.2 kV, $\Delta/Y_g/Y_g$ and 66.6 MVA, 110/12/12 kV, $Y/\Delta/\Delta$. Pipe type cables to Ottawa King Edward TS are also terminated to each of these HV circuits at the station. The station supplies Ottawa Hydro loads through twenty-five 12 kV and eleven 4 kV feeders, which are grouped either in ducts or directly buried inside the station and outside the station they are carried on overhead poles.

job	file	date	report no.
18-126-404	813.521	March 23, 1987	87-84-K

The station fence grounding was upgraded in 1984 and the need to determine the adequacy of the station and fence grounding system was identified. The station grounding system does not have a uniform ground mesh. The complex network of underground distribution cables at the station tends to reduce the ground potential rise considerably but adequate models are not yet available to include this effect. As a result, design-type calculations of the station grounding system performance become complicated. The objectives of the tests were to check the adequacy of the existing grounding system performance at the station with respect to public safety and station security and to develop models to generalize the results. The tests were requested and funded by Design and Development Division - Transmission.

2.0 TEST PROCEDURE

Simulated fault current tests were completed on June 19, 1986 at Overbrook TS to measure the station grounding system performance. As shown in Figure 1, 115-kV circuit K1R between Overbrook TS and Riverdale TS was taken out of service and the line grounding switch at Riverdale TS was closed to sink test current. A test current of 25 A at 120 V, 66 Hz from a gasoline-powered generator was injected into three parallel phases of the remotely grounded test circuit. The following measurements were made at Overbrook TS:

(a) Station ground potential rise between a remotely grounded communication cable (to Queens Sub) and local station ground.

(b) A potential profile towards the west from the station in order to calculate the ground potential rise.

(c) Current splits on skywires, HV cable sheaths, distribution neutrals, communication cable sheaths and water pipe.

(d) Touch and step potentials at the station.

(e) Soil resistivity tests.

Figure 2 gives a layout of the station with respect to the grounding tests and shows approximate locations of the measurement points. Here, the distribution neutrals are grouped approximately in four directions for clarity. Potentials and currents were recorded with respect to $1.0\angle 0$ A injected current. A Solartron 1170 frequency network analyzer synchronized to the 66 Hz generator and capable of rejecting 60 Hz noise level was used in conjunction with a 6-channel

amplifier to measure the ratio of two inputs including phase angle. A portable 2-channel oscilloscope was used to check the interference level. Two Ritz clip-on 5 VA, 150:5A CTs with 0.66 Ω shunts were used to supply the Solartron reference signal and to measure current splits in various conductors. A large split core Annis CT of 2000:5A ratio with a 10 Ω shunt was used to measure current splits on the large distribution cable sheaths. A patch panel allowed rapid switching of test leads between potential and current measurements. Telephone style carbon protectors were used to limit the potential to local ground on the input wiring to the instrumentation in the event of a system fault. Heavy connections were made from the frame of the instrumentation to the truck body and station ground for personnel safety.

The Wenner method using a Megger DET-2 ground resistance tester was used to determine the soil resistivity at the station. A soil resistivity survey was done near the station entrance along the right-of-way.

Assistance was obtained from District Operations, Station and Lines Maintenance, Regional P&C, Transmission Operations and Ottawa Hydro Staff in applying for the above outage, making temporary connections to the isolated HV line, locating the various cable sheaths and communication pairs and in conducting the measurements.

3.0 TEST RESULTS

3.1 Measured Soil Resistivity

Table 1 shows the apparent resistivities calculated using equation 7.1 of the Grounding Guide/1/. A two-layer model was fitted to the first four data points. The last two points were rejected because the lower readings at the large probe spacings may be due to interference from the nearby fences.

3.2 Measured Ground Potential Rise

From the potential profile readings (Table 2), the ground potential rise was derived assuming two different models. Point current injection (or spherical electrode) was assumed for taking into account larger distances and the potentials were plotted against inverse distance. For potentials at rather closer distances a disk electrode geometry was applied to include proximity of the station. Here, a horizontal rescaling based on an inverse sine method was used for an equivalent station radius of 45 m/2/. For uniform soil resistivity, test

points give a straight line for each method and ground potential rise can be taken at the zero intercept. The ground potential rise was also measured on the remotely grounded communication cable and corrected to take into account an estimated shielding factor of about 0.9/-22. Additional correction factors were applied to compensate for mutual coupling between the potential leads and the distribution neutrals.

Table 3 shows the corrected measured results along with the modelled values. The profile measurements were made with respect to the station grid close to the test van located near K1R switch. Test current returning through the grid conductors at this location could result in a negative voltage at this point compared to other grid locations. Due to these non-uniform grid potentials, the ground potential rise from profile measurements should be conservative. For an ultimate station fault current of 9 kA, the GPR as measured using the communication cable would be about 215/41 V.

Table 1
Ottawa Overbrook TS
Measured and Model Fitted Soil Resistivities

Probe Spacing (m)	Measured Apparent Resistivity (Ω.m)
1	62.14
2	79.80
5	108.39
10	115.23
20	88.59
50	28.59
Fitted Two-Layer Model Parameters	
ρ_1 = 60 (Ω.m) ρ_2 = 120 (Ω.m) d = 1.2 m	

Table 2
Ottawa Overbrook TS
Measured Potential Profile West of Station

Distance From Station Centre (m)	Measured Potential (mV/A)
120	0.68
150	6.56
180	7.60
210	9.58
230	8.62
280	9.62

Table 3
Ottawa Overbrook TS
Ground Potential Rise (GPR)

GPR From	GPR (mV/A)
1) Measured Potential Profile	
a) Point-Current Injection	27.90/62
b) Disk Injection	27.20/62
2) Measured on Remotely Grounded Communication Pair	23.85/41
3) Modelled	30.08/58

3.3 Measured Touch and Step Potentials

Touch and step potential measurements were repeated at several locations at the station and the worst case is presented in Table 4 along with modelled values. For an ultimate station fault current of 9 kA, the measured station step and fence touch potentials are approximately 70/60 V and 140/-125 V respectively.

The fence potentials measured at several locations are given in Table 5. Figure 2 shows the approximate measurement locations.

3.4 Measured Current Splits

The measured current splits are given in Table 6 along with the modelled values. The current split measured on the communication cables was negligibly small. A total current of 1.08/-7 A was measured on the skywires, HV cable pipes, distribution neutrals and water pipe as compared to total 1.00/0 A injected current, without allowing for I_g. This discrepancy could be due to measurement errors. Therefore, the component of the station ground current presented in Table 6 under measurement was estimated from the measured GPR and calculated R_g.

Table 4
Ottawa Overbrook TS
Touch and Step Potentials

	Measured (mV/A)	Modelled (mV/A)
Station Touch Potential (Mesh Voltage)	-	10.35/58
Station Step Potential	7.78/60	3.61/58
Fence Touch Potential		
a) Outside Fence	8.89/-124	4.48/58
b) Inside Fence	15.61/-125	-

Table 5
Ottawa Overbrook TS
Measured Fence Potentials

	Measurement Location in Figure 2	Measured Potential (mV/A)
a) Between Station Fence (+) and Grid	3	26.64/62
	6	6.42/50
	7	6.07/-142
b) Between Private Fence (+) and Station Fence	8	14.62/51
	10	6.73/-14
c) Across Gates	4	14.14/-114
	8	6.91/-133
	9	20.47/-110
d) Fence Touch Potential*		
(i) Probe Outside Fence	3	8.89/-124
	5†	3.80/51
	7	2.77/44
	10	6.63/68
(ii) Probe Inside Fence	3	15.61/-125
	5	4.40/52

*Between the fence (+) and a ground rod approximately 1 m away.
†On south side of fence.

Table 6
Overbrook TS
Current Splits

Current Path	Measured (A)	Modelled (A)
Injected to K1R Phases	1.000/0	1.000/0
Skywires	0.148/1	0.092/66
HV Cable Pipes	-0.006/11	0.012/-25
Distribution Neutrals	0.938/-8	0.930/-7
Water Pipe	0.003/55	-
Station Ground	*0.037/41	0.047/58
Total	1.105/-6	1.000/0

*Estimated from measured GPR and calculated R_g as $I_g = GPR/R_g$

4.0 MODELLED RESULTS

Appendix A summarizes the formulas used in the calculations, other than those given in the Grounding Guide/1/ and IEEE Guide 80 /4/.

4.1 Soil Resistivity

The measured soil resistivity data was interpreted as a two-layer soil model using the method given in Appendix D of the Grounding Guide/1/. An equivalent soil resistivity of 93 Ω.m was obtained from the two-layer model for an estimated equivalent station radius of 45 m. The grounding calculations are based on an equivalent soil resistivity of 100 Ω.m.

4.2 Isolated Station Ground Resistance

The calculated station ground resistance, R_g at Overbrook TS is 0.64 Ω, based on an estimated equivalent station radius of 45 m and 1200 m of buried ground conductors (equation 3.3 of the Grounding Guide/1/).

4.3 Conductive Equivalent Circuit

Figure 3 shows the grounding system interconnections at Overbrook TS with respect to fault current splits and Figure 4 shows the conductive equivalent circuit for tested conditions. The conductive circuit impedances, Z_c were calculated as Carson's earth return self impedances which carry the conductive component of the fault current/2/. Note that the water pipe was neglected in the equivalent circuit since the measured split on the pipe was negligibly small.

For the two 5/16" steel skywires, an equivalent conductor earth return self impedance was calculated as $4.88\underline{/12}$ Ω/km. Assuming a tower footing radius of 2 m and footing spacing of 10 m the calculated tower footing resistance is 12 Ω. From the ladder network of the skywire self impedance and the tower footing resistance, the lumped conductive impedances Z_{c1} and Z_{c2} of the two skywires (with tower span lengths of 300 m and 245 m respectively), were calculated as $4.19\underline{/6}$ Ω and $3.79\underline{/6}$ Ω respectively. For skywire #1 (HV line K1R where the fault was simulated), a shielding factor, S of $0.97\underline{/-4}$ was calculated from the skywire self and mutual impedances which is the component of the fault current applied to the conductive equivalent circuit. The inductive component of the skywire current calculated as (1-S) I_f is $0.078\underline{/69}$ A.

The conductive circuit impedances of the HV cable pipes include Carson's earth return and internal ac impedances/3/. Both pipes run in parallel with approximately 1 m separation. The parallel circuit impedance Z_{C3} including the mutual effect was calculated as 2.57/83 Ω. At King Edward TS, with extensive distribution neutrals, the station ground impedance should be very small and was neglected compared to the pipe impedance.

For the thirty six OHES distribution feeders, the net impedance Z_{C4} of 0.032/65 Ω was calculated based on the parallel combination of all the feeder neutrals. Between the station and the overhead pole lines, the feeder cables are grouped either in ducts or directly buried. The Carson's earth return impedances for each section of a feeder neutral were calculated separately and combined together to get the total impedance of a circuit. For cables in ducts a GMR of 0.2 m was assumed and for direct buried groups, the GMR was calculated assuming a spacing of about 300 mm between cables. It is assumed that there are no skywires on the distribution poles although these are sometimes used by Ottawa Hydro. The feeder neutrals on poles were assumed to consist of 21 mm^2 (#4) copper conductor for 4 kV feeders and 85 mm^2 (3/0) ACSR conductor for 12 kV feeders. Assuming distribution taps at 200 m spacing along the main feeders with the first tap at 300 m from the station and service drops at 20 m spacings gives feeder neutral impedances of 0.666/65 Ω for a 4 kV neutral and 0.736/61 Ω for a 12 kV neutral. Here a service drop ground resistance of 10 Ω due to water connection to each house was assumed. The ground rod resistance at distribution transformers was neglected since it is normally large compared to 10 Ω.

From the network of Figure 4, the resulting interconnected station ground impedance is 0.031/62 Ω.

4.4 Modelled Current Splits

The conductive equivalent circuit in Figure 4 was solved for an injected station fault current of 1.00/0 A. The calculated current splits are given in Table 6. Note that the skywire current is the sum of conductive and inductive components.

4.5 Modelled Ground Potential Rise

From the resulting station ground current split I_g, the ground potential rise (GPR) at Overbrook TS is 30.08/58 mV/A, calculated as $I_g R_g$ where R_g is the isolated station ground resistance. For an ultimate fault current of 9 kA, the calculated GPR is about 271/58 V.

4.6 Modelled Station Touch and Step Potentials

The station touch (mesh) and step potentials were calculated using equation 3.6 of the Grounding Guide/1/ and equation 75 of IEEE Guide 80 /4/ respectively. These equations apply to a uniform ground grid mesh. However, at Overbrook TS, the ground grid is irregular in layout and values based on average spacing was used for the parameters in these equations. Therefore the calculated results may not be conservative. The calculated voltages are given in Table 4. For an ultimate station fault current of 9 kA, the modelled station touch and step potentials are 93/58 V and 33/58 V respectively.

4.7 Modelled Fence Touch Potential

Touch voltage to the public outside the fence was calculated as 4.48/58 mV/A assuming that the station fence is not connected to the main station grid and using equation 3.11 of the Grounding Guide/1/. This is about 40/58 V for an ultimate fault current of 9 kA. Table 4 compares the calculated value with the measured result. Here also, the calculated value may not be conservative due to the irregularity of the station grid as explained above.

5.0 DISCUSSION OF RESULTS

5.1 The extensive multigrounded distribution system is the most significant factor in reducing the station ground impedance to 0.031/62 Ω. The calculated isolated station ground resistance is 0.64/0 Ω.

5.2 The LV distribution system with its many parallel feeder neutrals carries about 93% of the fault current entering the station grounding system and only about 5% enters the station ground. As a result the station ground potential rise is considerably reduced and is well under the recommended limit of 3 kV for an ultimate fault current of 9 KA on circuit K1R. Therefore, for stations with an extensive network of distribution cables, the distribution neutrals should be considered in detail to derive station ground potential rise.

5.3 The tolerable limits of touch and step potentials calculated using equation 2.4 and 2.2 of the Grounding Guide/1/ are 181 V and 263 V for bare soil surface. The station touch and step potentials for an ultimate station fault current of 9 kA are both within the tolerable limits. The modelled touch and step potentials

are lower than the measured results possibly because the model is based on average spacing for the irregular grid geometry of the station and may not be conservative.

5.4 Negative currents were measured on HV cable pipes, but magnitudes matched calculated values. The measurements were repeated and polarities checked without finding the cause for this anomaly.

5.5 The small sized steel skywires at the station result in a poor shielding factor and hence about 97% of the total fault current enters the station grounding system which includes the conductive current paths as shown in Figure 4.

5.6 It was noticed towards the end of the tests that the station grid close to the test van located near K1R switch (location 1 in Figure 2) was at a negative potential with respect to the grid near the metalclad switchgear (location 2 in Figure 2). Test current injected to remote ground returning through grid conductors at the test location probably caused the negative voltage. The potential profile measurements were made with respect to this negative grid point and therefore may be conservative.

5.7 Between the station fence and main station grid a potential of about 27 mV/A was measured on the south section of the fence and about 6 mV/A was measured on the west and north sections. The measured result may include induction. Further, the station grid may not be at a uniform potential as explained above. Therefore it cannot be verified from these measured values that the fence is isolated from the main station grid. The measured touch potential along the station fence also varied at different locations (Table 5). The maximum measured and modelled fence touch potentials for a fault current of 9 kA are both under the tolerable touch voltage limit for the station.

5.8 Private metallic fences are run within 1 - 1.5 m of the station fence on the south, north and west sides of the station (Figure 2). Private and station fences should not be interconnected. The Bell Telephone fence appears isolated near point 10 but bonding of the main entrance gate may cause it to become part of the North station fence. A maximum of about 15 mV/A was measured between a private fence and station fence near point 8 and across a private gate at point 4. Closing of this gate would connect the station fence to an extensive network of private fences (Table 5). For an ultimate station fault current of 9 KA, this is about 135 V which is approaching the tolerable touch voltage limit of 181 V.

5.9 A potential of 20.47/-110 mV/A (about 184 V for 9 kA) measured across the station entrance gate (Table 5) indicates that the buried wire across the gate as shown in the station drawing #407275ES may not be continuous.

6.0 CONCLUSIONS

6.1 The equivalent soil resistivity for an estimated station radius of 45 m at Overbrook TS is about 93 Ω.m based on a two-layer soil model obtained from Wenner test data.

6.2 The isolated station ground resistance calculated from the ground grid geometry is 0.64 Ω. The modelled interconnected station ground impedance is 0.031/62 Ω, mainly due to the parallel combination of the several interconnected distribution neutrals.

6.3 The ground potential rise at Overbrook TS as measured via a communication cable is 23.85/41 mV/A which would be about 215/41 V for an ultimate station fault current of 9 kA on the HV circuit K1R. This is well under the recommended limit of 3 kV.

6.4 For stations with extensive LV feeder cables, the distribution neutrals are more important than the station ground resistance in deriving the station ground potential rise. Models have been developed to estimate the station ground potential rise.

6.5 The station touch and step potentials for an ultimate station fault current of 9 kA are within the tolerable limits calculated for the station.

6.6 The station fence touch potential to the public outside the station for the above fault current is within the tolerable touch potential for the station.

6.7 The station grid near the test current injection location was found to be at a negative potential with respect to another grid location possibly due to the injected test current returning in the grid conductors. In future measurements, reference grid points should be chosen sufficiently away from test current injection location in order to reduce the effect of this non-uniform grid potential.

6.8 Measurements could not clearly establish whether the station fence is bonded to the main station grid. The measured potentials varied along the fence.

6.9 Measurements show that the station gates are not properly bonded to encompass the gate swing area.

6.10 Private metallic fences are run in close proximity to the station fence. At some locations, the potentials between the station fence and private fence for a fault current of 9 kA are approaching the tolerable touch voltage limit for the station.

7.0 RECOMMENDATIONS

7.1 The buried bonding wire across all station gates should be checked. A proper buried mat should be installed encompassing the gate swing area and connected to the fence grounding system.

7.2 Crushed stone should be provided on the soil surface around station fences. Station and private fences should not be interconnected.

7.3 Distribution neutrals should be considered in detail in the design of grounding systems for stations with extensive interconnected distribution feeders. Preliminary models have been developed for this purpose and are being reviewed by Electrical Research Department.

Approved:

A.F. Baljet
Manager
Electrical Research Dept

Submitted:

R.P. Pillai
Engineer
System Studies Section

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2. E.P. Dick, "Modeland TS - Grounding System Resistance and Soil Potential Profile", Ontario Hydro Research Report 82-325-K, February 28, 1983.

3. E.P. Dick, "Strachan TS Grounding System Calculations", Ontario Hydro Research Report 83-433-K, November 7, 1983.

4. IEEE Standard 80, IEEE Guide for Safety in AC Substation Grounding, 1986 Revision.

5. P. Pillai, "Toronto Cecil TS Grounding System Studies", Ontario Hydro Research Report No. 86-155-K, January 25, 1986.

APPENDIX A
SUMMARY OF FORMULAS USED IN GROUNDING CALCULATIONS

1. Conductor Earth Return Self Impedance, Z_s

$$Z_s = R_s + jX_s \ (\Omega/km) \tag{1}$$

$$R_s = 0.059 + R_{ac} \ (\Omega/km) \tag{2}$$

$$X_s = 0.0377 \ln \left(\frac{8440 \ \rho_s}{GMR^2} \right) \ (\Omega/km) \tag{3}$$

Where, R_{ac} = conductor ac resistance (Ω/km)
ρ_s = soil resistivity (Ω.m)
GMR = conductor geometric mean radius (m)

For pipes or shields, R_{ac} and X_{ac} (conductor internal reactance added to X_s) are calculated as shown in reference/3/.

2. Conductor Earth Return Mutual Impedance, Z_m

$$Z_m = R_m + jX_m \ (\Omega/km) \tag{4}$$

$$R_m = 0.0377 \tan^{-1} \left(\frac{8440 \ \rho_s}{GMD^2} \right) \ (\Omega/km) \tag{5}$$

$$X_m = 0.0377 \ln \left(\frac{8440 \ \rho_s}{GMD^2} + 1 \right) \ (\Omega/km) \tag{6}$$

Where, ρ_s = soil resistivity (Ω.m)
GMD = geometric mean distance between conductors (m)

3. Tower Footing Resistance, R_t

$$R_t = \frac{\rho_s}{2\pi} \left[\frac{1}{r} + \frac{2.707}{w}\right] \ (\Omega) \qquad (7)$$

Where, ρ_s = soil resistivity (Ω.m)
r = equivalent footing radius (m)
w = footing spacing (m)

4. Chain Impedance of Skywires, Z_c

$$Z_c = \sqrt{Z_s \ell R_t} \ (\Omega) \qquad (8)$$

Where, Z_s = conductor earth return self impedance (Ω/km)
ℓ = span length (km)
R_t = tower footing resistance (Ω)

5. Station Earth Potential to Remote Ground $V_{(x)}$

Refer to /5/.

For disk-like electrode in uniform earth,

$$V_{(x)} = \frac{\rho_s I_g}{2\pi r} \sin^{-1}\left(\frac{r}{x}\right) \qquad (9)$$

Where, ρ_s = soil resistivity (Ω.m)
I_g = ground current (A)
r = station radius (m)
x = distance from station centre (m)

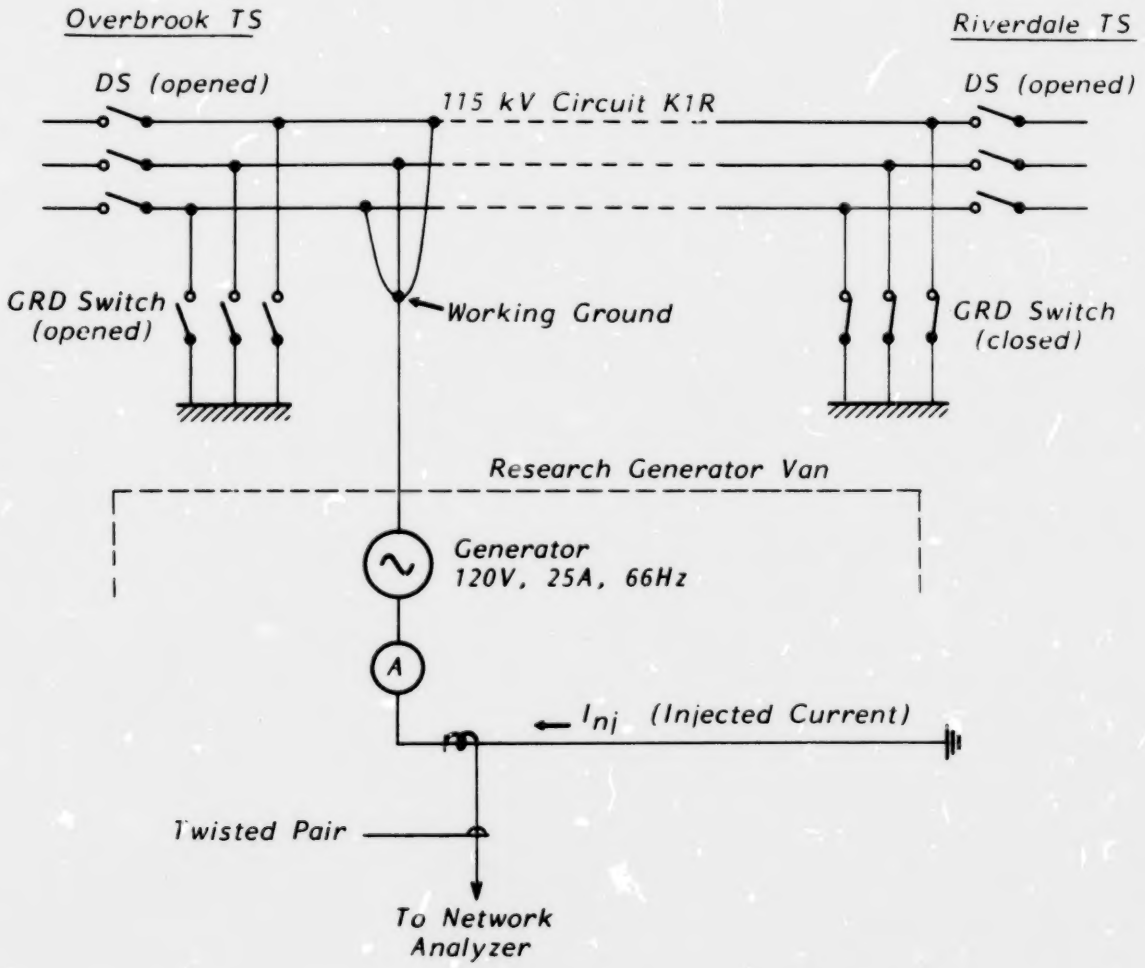

FIGURE 1

OTTAWA OVERBROOK TS
GROUNDING TESTS-FAULT SIMULATION CIRCUIT

174223-RD

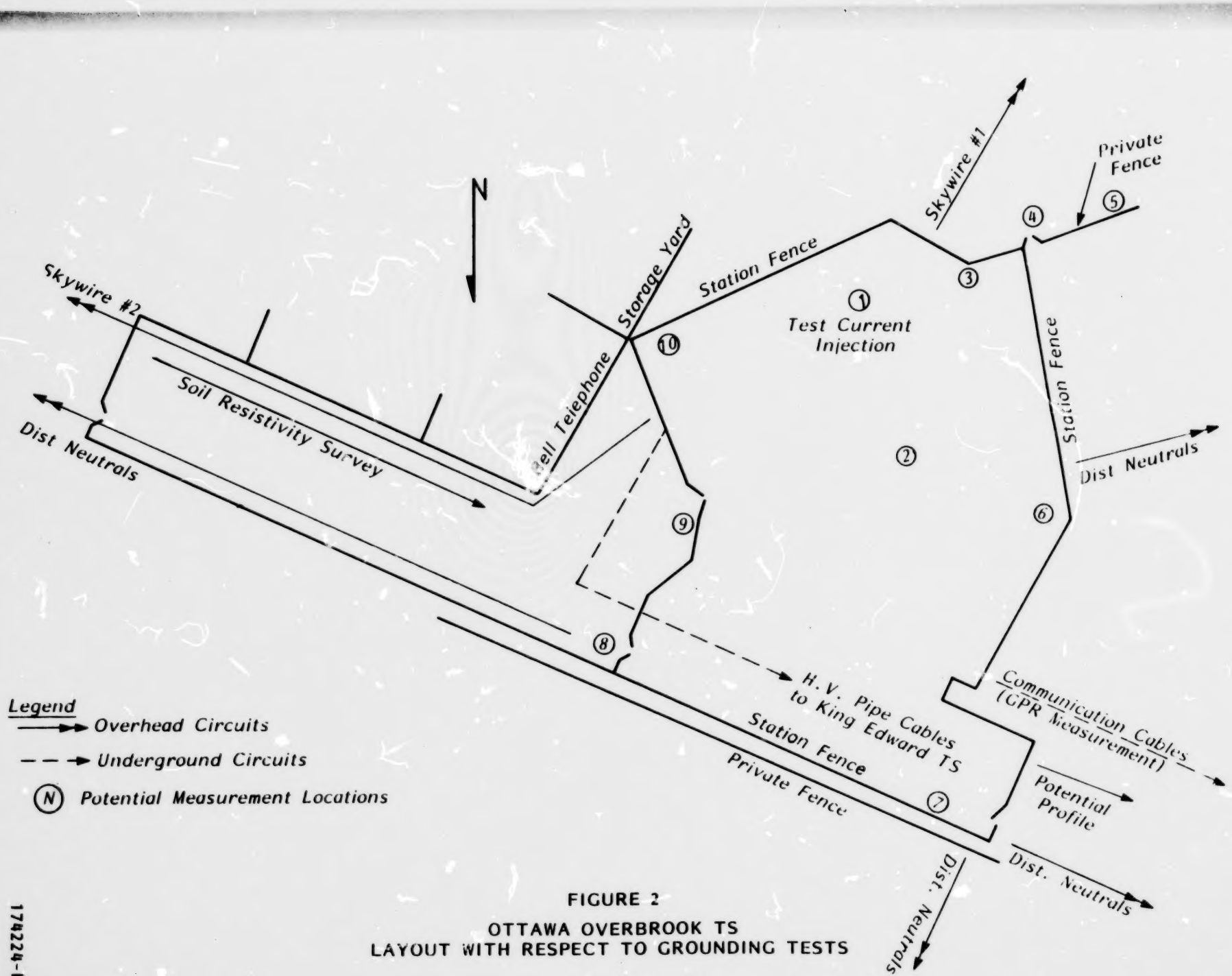

FIGURE 2

OTTAWA OVERBROOK TS
LAYOUT WITH RESPECT TO GROUNDING TESTS

174224-RD

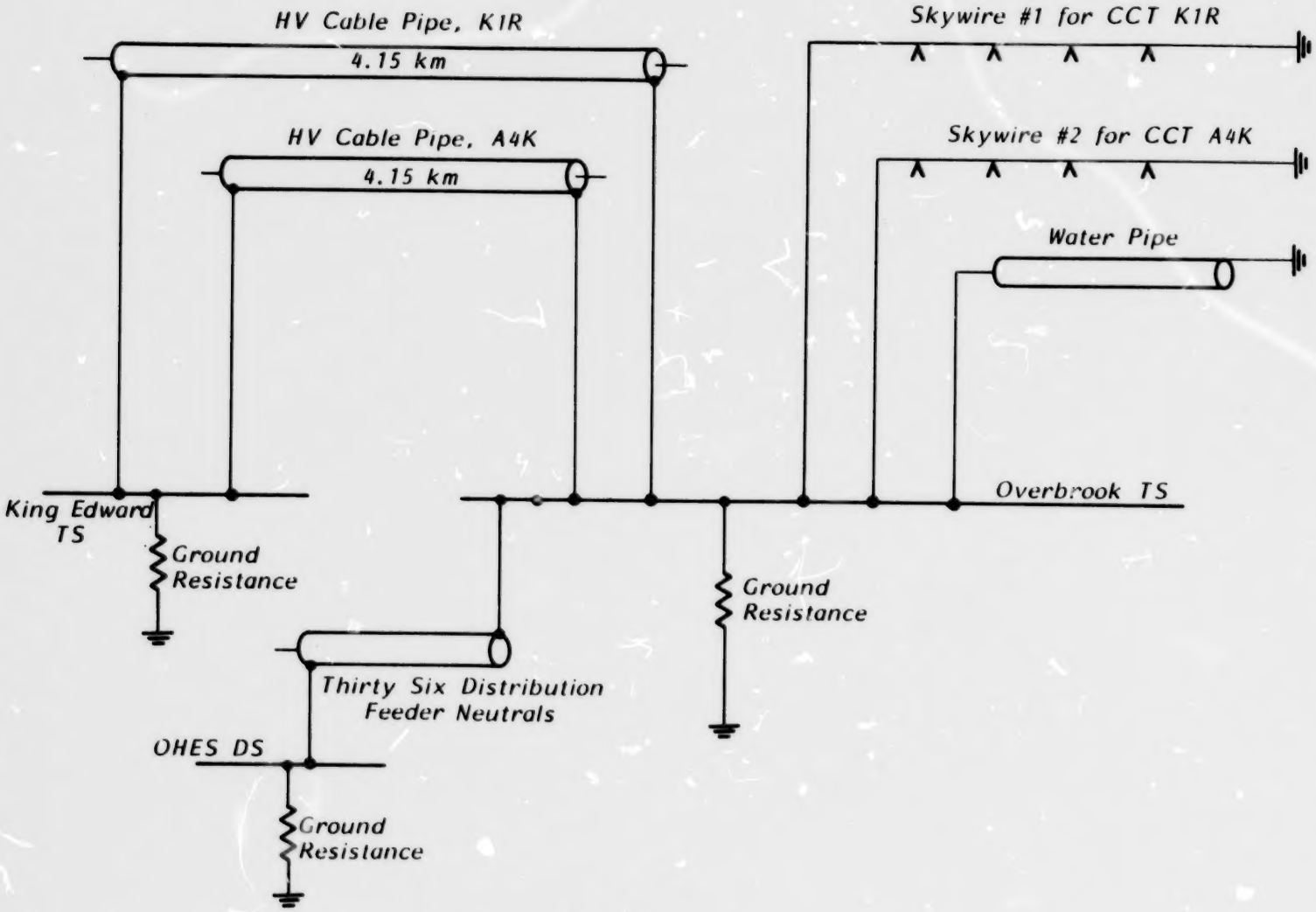

FIGURE 3

OTTAWA OVERBROOK TS
GROUNDING SYSTEM INTERCONNECTIONS

174225-KD

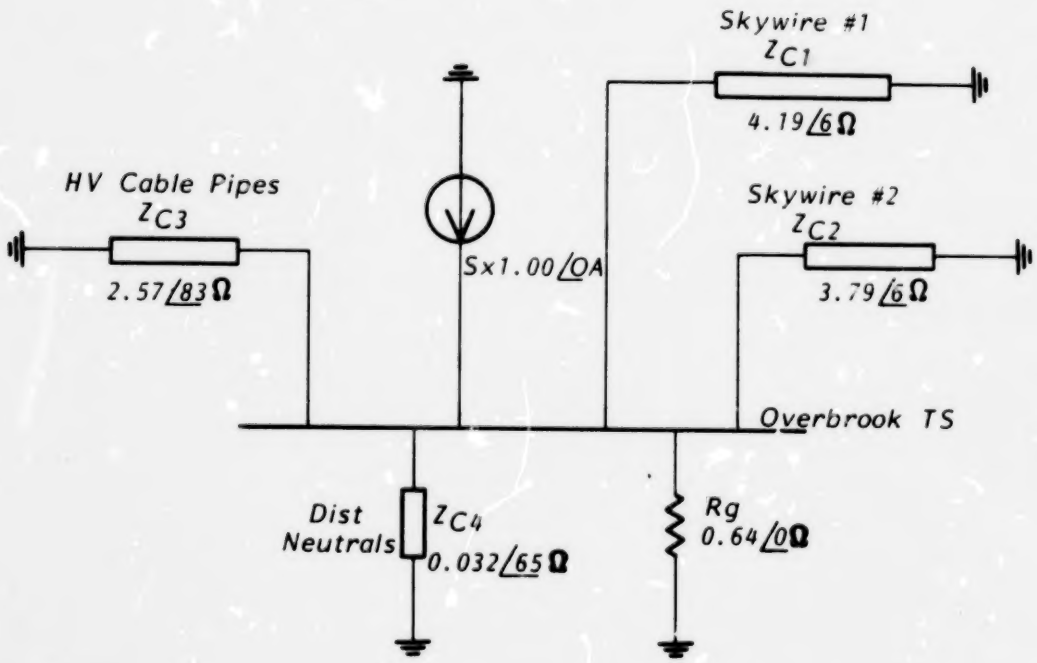

FIGURE 4

OTTAWA OVERBROOK TS
CONDUCTIVE EQUIVALENT CIRCUIT FOR HV STATION FAULT

DISTRIBUTION

Mr. N.M. Thompson	Des & Dev - Transmission	H9 C1
Mr. J.L. Bender	Des & Dev - Transmission	H9 A7
Mr. H.H. Toda	Des & Dev - Transmission	H9 D7
Mr. B.A. Oliver	Des & Dev - Transmission	H9 A27
Mr. J.H. Midgley	Des & Dev - Transmission	H8 A27
Mrs. A.M. Sahazizian	Des & Dev - Transmission	H8 A18
Mr. S.J. Arnot	Des & Dev - Transmission	H8 A21
Mr. A. Renzi	Des & Dev - Transmission	H8 A22
Mr. G.W. Jackson	Des & Dev - Transmission	H10 A19
Mr. L.J. Perfecky	Des & Dev - Transmission	H10 A18
Mr. D.S. Chong	Des & Dev - Transmission	H10 B20
Mr. L.V. Doran	Transmission Operations	U9 A5
Mr. W.E. Palmer	Transmission Operations	U9 A1
Mr. H.H. Tan	Transmission Operations	U9 B4
Mr. H.W. Parish	Transmission Operations	U7 E5
Mr. J.J. Clifton	Transmission Operations	U7 E4
Mr. J.S. Hartill	Transmission Operations	U10 A5
Mr. R.H. Cook	Transmission Operations	U10 E3
Mr. R.L. Boon	Transmission Operations	U10 A5
Mr. A.E. Martin	Transmission Operations	U7 A1
Mr. L.J. Rubino	System Planning	H4 G25
Mr. E.G. Neudorf	System Planning	H4 D27
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Mr. M.E. Bedford	Eastern Region, Belleville	
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